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Title: POROUS METALS AND METAL
COATINGS FOR IMPLANTS

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TRANSMITTAL OF PRIORITY DOCUMENTS

Applicants submit herewith are certified copies of European Patent Application Nos. EP 01200587.2 and EP 01202062.4, from which the above-referenced U.S. patent application claims priority. No fee is due. Please apply any other charges or any credits to Deposit Account No. 19-0733.

Respectfully submitted,

Date:

August 2, 2004

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The attached documents are exact copies of the European patent application described on the following page, as originally filed.

Les documents fixés à cette attestation sont conformes à la version initialement déposée de la demande de brevet européen spécifiée à la page suivante.

Patentanmeldung Nr. Patent application No. Demande de brevet n°

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Der Präsident des Europäischen Patentamts;
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For the President of the European Patent Office

Le Président de l'Office européen des brevets
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Bezeichnung der Erfindung/Title of the invention/Titre de l'invention:
(Falls die Bezeichnung der Erfindung nicht angegeben ist, siehe Beschreibung.
If no title is shown please refer to the description.
Si aucun titre n'est indiqué se referer à la description.)

Porous metals for implants

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Title: Porous metals for implants

The invention is directed to a method for preparing porous bodies, suitable for the preparation of porous metal articles, as well as to these porous metal articles *per se*. More in particular the invention is directed to the use of these porous metals in the preparation of medical items, such as implants or
5 scaffolds in tissue engineering.

Because of their excellent characteristics, titanium, tantalum and alloys thereof find use in medical devices, such as implants. These materials provide good biocompatibility, are lightweight, have a high strength, and superior corrosion resistance. Great effort has been given to the application of
10 these materials in the production of medical equipment, such as dental implants, clips for blood vessels, artificial bones, artificial joints, *etc.* Most of these applications use the dense phase of these metals. The use of powder metallurgy for fabrication of orthopedic joint replacement implants was first reported in the mid-1960s. Porous titanium was first used for dentistry in
15 animals in American Medical Center of Luke and University of Chicago in 1969.

Regeneration of skeletal tissues has been recognized as a new means
for reconstruction of skeletal defects arising from abnormal development , trauma, tumors and other conditions requiring surgical intervention.
20 Autologous bone grafting is considered as the golden standard of bone transplantation with superior biological outcomes. However, autologous bone stocks are limited and often insufficient, particularly when large skeletal defects are encountered. As surgical techniques and medical knowledge continue to advance, there is an increasing demand for synthetic bone
25 replacement materials. Variation of the scaffold design as three-dimensional superstructures has been demonstrated as an approach to optimize the functionality of bone regeneration materials so that these materials may be custom designed for specific orthopedic application in the form of void fillers,

implants, or implant coating. In an attempt to develop a skeletal cell and tissue carrier, which could provide optimal spatial conditions for cell migration and maintenance by the arrangement of structural elements such as pores and fibers, the feasibility of using "live" material is under investigation. Such live
 5 material could take the form of an open-porous implant system together with living tissue. This technique is also referred to as hard tissue engineering.

Several methods are already known to make porous metals, such as titanium. Examples of these known methods are isostatic pressing (ISP) sintering, rolling sintering, loose packed sintering and fiber-wired sintering. In
 10 general, according to these known methods, titanium particle are mixed together with a binders or loosely packed, and subsequently sintered. The packing of the particles than leaves a porous structure. However, the porous metals made by these known methods have shortcomings. Usually the porosity is too low, *i.e.* below 50%. Also the pore size is generally too small, the
 15 maximum pore size being about 300 μm .

Another method to make porous metals, such as titanium is hammer-pressing metal fiber. Although the porosity obtained by this method is above 70%, the strength is generally too low and the pore size is still too small.

20 For use as implants, the pore size and porosity are important for the cells to grow inside after implantation. In general, the porous metal should, apart from the above-mentioned chemical requirements of good biocompatibility, lightweight and superior corrosion resistance, meet the following requirements: the porosity should be 50% or more, the average pore
 25 size should be at least 400 μm , preferably at least 500 μm . Preferably the average pore size should not exceed 800 μm . In addition, the pores should be interconnected and the compressive strength should be sufficient for load-bearing purposes. In particular, the mechanical compressive strength of porous titanium alloy should be at least 5 MPa.

Further, US-A-6 136 029 discloses a process for the preparation of ceramic porous bone substitute material. This known process is, however, not suitable for the preparation of metal articles. The pyrolysis and subsequent sintering according to this known method, will give rise to formation of
5 undesired metal compounds, such as metal nitrides and oxides, in particular on the outer surface of the porous articles. For use as implants, the presence of these compounds, in particular on the outer surface, is not acceptable, because the formation of metal nitride or oxides will give rise to a decrease of mechanical strength. Metal nitrides or oxides such TiN or TiO₂ compounds are
10 formed in the presence of air (N₂/O₂/H₂O) at the high temperature reached during sintering of metals (e.g. 1250°C). Titanium is a very reactive metal and can react with nitrogen, oxygen or water to form nitride or oxide at temperature as low as 700°C according to the following equations:



Up until now, it has not been possible, or only with great difficulty, to provide porous metals, suitable for implants, which meet the above-mentioned requirements and/or do not suffer from the above-mentioned shortcomings. It is an object of the present invention to provide for a method,
20 with provides for a substantial improvement regarding the above-mentioned requirements and drawbacks in respect to the methods of the prior art.

The present inventors have found that this object can be met by preparing porous bodies, from which metal articles can be made, by the so-called slip casting process. The slip casting process comprises the preparation
25 of a body by the impregnation of a pyrolysable foam material, such as a polymer, with a slurry of metal particles, and subsequent pyrolysis of the foam material. This may subsequently be followed by sintering of the body. Therefore, in a first embodiment, the present invention is directed to a method for preparing a porous body, suitable for the production of a porous metal
30 article, comprising the steps of providing a polymeric foam, which foam is

impregnated with a slurry of metal particles, drying the impregnated foam, followed by pyrolysis in the presence of metal hydride particles.

Furthermore, the present invention provides a method for preparing a porous metal article comprising sintering of the body thus obtained, which
5 sintering is carried out in the presence of metal hydride particles.

The term "presence" as used herein, is to be interpreted in its broadest sense, *viz.* it is sufficient to carry out the pyrolysis or the sintering in an environment, in which environment the metal hydride particles are also present. Preferably the metal hydride is substantially not in contact with the
10 impregnated foam or the body. This may *e.g.* be effected by placing the sample to be pyrolyzed or sintered in an oven, while the metal hydride is present in a different location of the same oven. It was found that the presence of the metal hydride particles is an important aspect of the method of the present invention, since these particles prevent the formation of undesired metal
15 compounds, such as oxides and/or nitrides (*e.g.* titanium oxide and/or titanium nitride). Presence of these undesired metal compounds would make the articles unsuitable for medical use, *e.g.* as implants. In this respect it is stressed that although the pyrolysis and subsequent sintering are usually and preferably carried out in vacuum (in practice this means pressures of about 0.5 mPa up to
20 several Pa), the presence of reactive gases, in particular of oxygen and nitrogen from air, as well as water, can never completely be avoided, even not if these steps are carried out in an inert gas, such as argon. In addition, the slip casting method involves the impregnation of a foam material with a slurry of metal particles, as a result of which air, water and/or other contaminants
25 may become captured in the impregnated body, which contaminants cannot be removed by *e.g.* lowering the pressure and/or flushing with inert gas.

As a consequence, if no countermeasures are taken, the formation of undesired metal compounds is inevitable. Presence of these undesired metal compounds is already detrimental in very low concentrations.

Without wishing to be bound by theory, it is assumed that the metal hydride particles are much more reactive with respect to contaminants, such as air and water, than the metal particles. As a result, the metal hydride particles act as a scavenger and react with these contaminants under pyrolysis or sintering conditions, so that the metal particles are protected against undesired nitration or oxidation. In addition, the fusion of the metal particles during sintering is enhanced by the absence of the metal nitrides and oxides, resulting in an increased mechanical stability of the final article.

The metal hydride particles, which serve as a scavenger may be introduced by impregnating the foam with a slurry of these metal hydride particles. For convenience, it is preferred that the metal hydride particles are present in the same slurry as the metal particles. As was stated above, it is however preferred not to provide the metal hydride particles in a slurry in the foam, but to provide these particles separately from the impregnated foam, *viz.* on a different location in the same environment.

The slurry of metal particles, and optionally metal hydride particles is prepared by mixing said particles with water under stirring until a homogenous slurry is obtained. Generally, a concentration will be chosen between 50% and 80wt%, preferably between 55 and 75wt%, based on the weight of the slurry.

In order to obtain a stable slurry, the addition of a binder is preferred. The concentration of binder is an important measure for controlling the viscosity of the slurry. With the increase of the amount of the binder, the sedimentation rate of the particles decreases because of the increasing viscosity of the slurry. It has been found that the optimal viscosity ranged from 4000 cp to 12000 cp, if the viscosity is too high, it is difficult to remove the extra slurry after impregnation. Suitable concentrations for the binder are 2-15 wt.%, preferably 4-9 wt.%. The criteria for selecting the binder material are that the binder should not react with metal powder and that it should be removed completely after the sintering of the samples. Suitable binders are

e.g. PEG4000, methylcellulose and/or carboxyl methyl cellulose (CMC), polyolefins such as polyethylene or polypropylene, ethylene vinyl acetate, styrene group resins, cellulose derivatives, various types of wax; paraffin, and the like.

5 Particularly suitable metal particles are made from titanium, tantalum, titanium alloy, tantalum alloy, and mixtures thereof. Other suitable metals include cobalt-chromium, stainless steel, nickel and nickel alloy, zirconium and niobium.

10 The metal hydride particles are composed of titanium hydride, tantalum hydride, *etc.* Preferably the hydride is based on the same metal as the metal used to obtain the body. Metal hydrides are commercially available, usually in the form of a powder, having a particle size of about 20-120 μm . To assist the sintering, the amount of metal hydride employed is about 5-10 wt.%, based on the weight of the porous body. To assist the pyrolysis the same
15 amounts may be used, based on the weight of metal particles present in impregnated foam.

 Polyurethane (PU) is a very suitable polymeric material to be used according to the present invention, since it has an excellent pore structure. Preferably, PU foam having a pore size of 500-2000 μm is used. Although other
20 polymers, such as polymethyl methacrylate, polyether, polyester, and mixtures thereof may be used as well, these polymers are less suitable, because it was found that these polymers do not pyrolyze as well as PU and/or have a less advantageous pore structure.

 Apart from the binder, other additives may be used. These additives
25 comprise deflocculants, such as Dolapix™.

 Furthermore, viscosity modifying agents may be used, to control the viscosity of the slurry. Preferably the viscosity of the slurry is from 4000 cP to 12000 cP, as measured on a Brookfield viscometer, using a HA5 spindle at a spindle speed of 20 rpm.

As a further additive, pH-modifying agents, such as ammonia may be employed to control the solubility of the titanium material..

Average particle size and particle size distribution of the metal particles are important parameters in preparing the articles of the present invention. Generally, the sintering of fine powders is easier than the sintering of coarse powders. For this reason, fine powder with diameter smaller than 5 μm would be desirable, but are however, difficult to obtain commercially. Particles larger than about 120 μm tend to segregate in the slurry and may hamper the formation of a homogeneous suspension. Preferred average particle sizes for the metal are from 5-100 μm , even more preferably from 10-50 μm . Metal particles which are commercially readily available have a particle size of 325 mesh (44 μm).

After preparing the slurry was, the polymeric foams are contacted with the slurry, so that the foam becomes soaked with slurry. Excessive slurry may be removed, *e.g.* by applying pressure by squeezing. Subsequently, the slurry-loaded foams may be dried, typically at 50-150 °C. After a suitable period of time of drying at elevated temperature, *e.g.* 1-5 hours, the sample may be further dried at room temperature, *e.g.* for 1-2 days.

It is preferred to carry out the drying (as well as the pyrolysis and/or the sintering steps, described in more detail below) in a vacuum oven. Such an oven may be programmed to run a predefined temperature/pressure program. When the temperature of the oven rises and/or when the pressure is decreased, drying of the material will take place, by which water is evacuated from the impregnated foam. Drying is continued till essentially all the water and other volatile substances are removed from the impregnated foam. Typically, the drying is carried out at the above-mentioned temperatures and at pressures of about 0.001 - 0.1 mbara.

After drying, the sample is subjected to pyrolysis, in order to remove the polymeric foam and binder (and other organic or pyrolysable material, if present) from the sample to yield a porous body of metal particles. The

removal of binders and foam is performed through heat processing under a non-oxidative atmosphere. During the heat processing of porous titanium, the rate of removal of binder and PU is an important parameter. Evaporating the binder too fast, may cause "blisters" to form, while evaporating the binder too slow may causes parts of the sample to collapse. Pyrolysis is preferably carried out under vacuum or reduced pressure conditions, typically 10^{-1} to 10^{-6} mbara and preferably at about 10^{-2} - 10^{-3} mbara. The pyrolysis is preferably carried out at a temperature from about 50-650°C, and even more preferably at about 150-550°C. Preferred time periods for removing the binders and foam range from about 8 to 72 hours, even more preferably from about 12 to 16 hours.

After removal of binders and foams and optionally other material by the pyrolysis step, the resulting body is ready for final sintering, if desired. The sintering may be performed in one or multiple steps. It is preferred that the sintering is carried out at a temperature of about 700-1500°C, preferably for about 10-26 hours. More preferably the sintering is carried out at a temperature of about 800-1400°C, preferably for about 12-18hours. The sintering atmosphere is a non-oxidation atmosphere, proceeding, for example, in argon or other inactive gases, under a vacuum or reduced pressure conditions, about 10^{-3} to 10^{-6} mbara.

It is noted that suitable durations for the respective drying, pyrolysis and sintering steps, depend on the size of the foam materials and may vary accordingly, the above-mentioned preferred values for the these durations being given for a typical sample size of several cm. Depending on the specific case, each of the drying, pyrolysis and sintering step is generally carried out in a period of time ranging from several hours to several days.

In order to further improve the mechanical strength of the article produced, addition of ceramic particles to the slurry may be advantageous. Suitable ceramic particles are for instance zirconium oxide particles.

In order to prepare articles that may be used as implants, the foam may be formed into the desired shape and size, e.g. by cutting, after which the

method of the invention is carried out to produce a sintered metal body. A dimensional shrinkage of 3-5% will normally occur in the drying and sintering stage, which may be corrected for in cutting the foam that is used as starting material. The sintered metal body may be further machined with usual means, such as drilling, milling, *etc.*, to give it its desired shape and size.

According to the method of the invention, it is possible to produce articles that have a porous metal structure with a porosity of at least 50%, having a mean pore size of at least 400 μm , wherein the pores are interconnected. The porous metal articles of the invention have a compressive strength ranging from 5 MPa up to 40 MPa, or even higher. Strength is obviously related to porosity. In the case of 80% porous titanium alloy, a compressive strength of 10 MPa or higher may be obtained in accordance with the invention, which is suitable for applications in implants. Typically, 50-90% porous implants can be provided, having a compressive strength ranging from 5-40 MPa. The mechanical compressive strength which may be obtained in accordance with the present invention is sufficient for load-bearing purposes. The articles of the invention are therefore particularly suitable for use as an implant, such as bone replacement material or scaffolds (*viz.* porous structures to which living tissue may be applied *in vitro* and which are subsequently implanted).

The invention will now be illustrated by the following examples.

Example 1

Titanium powder containing particles having an irregular shape and an average particle size of 325 mesh ($< 44 \mu\text{m}$) was obtained from the Beijing Non-Ferrous Institute in China. The chemical composition of the powder was as follows:

Element	N	H	O	C	Fe	Ti
W/w %	0.06	0.06	0.5	0.05	0.15	balance

A slurry was prepared by mixing the titanium powder, with a 25% ammonia solution (Merck), Dolapix (Zschimmer & Schwarz GmbH, Germany) and methylcellulose (Dow U.S.A) in the amounts given in Table 1 under stirring. Stirring was continued until homogeneous slurry was obtained.

5

Table 1 Composition of titanium slurry for Example 1

Ingredient	Quantity (g)	Wt. %
Demi water	100	30
Dolapix CE64	4	1.2
Ammonia (25%)	7	2.2
Methylcellulose	2	0.6
CMC	0.46	0.15
Ti powder	222	65
Total	333	

Polyurethane foam was soaked in the slurry and squeezed by hand to remove extra slurry. After drying, the sample was placed in a vacuum furnace on top of 16 g of titanium hydride (obtained from RaoTai China), the titanium hydride being present on the bottom of the furnace. The furnace was set to follow a preset temperature and pressure program. The temperature program comprised heating the impregnated foam to remove binders and the foam during about 1000 minutes during which the temperature increased from 25 to about 350°C. The pyrolysis was carried out at a pressure of 0.01 mbara. Directly following the removal of the binder, the temperature was risen to 1250°C and the product was sintered at this temperature during about 140 minutes. The sintering was carried out at a pressure of 0.00002 mbara. Following the sintering the heating was stopped and the pressure was normalized.

Of the obtained porous titanium, microscopic photographs were taken as shown in Fig. 1-5. Fig. 1 shows the structure under an optical microscope with a magnification of 20x. Fig. 2 shows the structure of porous titanium under SEM, and Fig. 3 shows the strut of porous titanium. Figure 4 shows microstructure at a magnification of 500x, and Fig. 5 shows the same

microstructure at a high magnification of 1000x. The pictures show a interconnected system of regularly shaped pores.

Example 2

- 5 Titanium alloy powder having an spherical shape and an average particle size of 325 mesh ($< 44 \mu\text{m}$) was obtained from the Northwest Non-ferrous Institute in China. The chemical composition of the powder was as follows:

Element	N	H	O	C	Fe	Al	V	Ti
W/w%	0.05	0.015	0.2	0.08	0.3	5.5-6.5	3.5-4.5	balance

- 10 A slurry was prepared by mixing the titanium alloy powder, with a 25% ammonia solution (Merck), Dolapix (Zschimmer & Schwarz GmbH, Germany), PEG4000 (Merck) and Carboxymethylcellulose (Merck) in the amounts given in Table 2 under stirring. Stirring was continued until homogeneous slurry was obtained.

15

Table 2 Composition of titanium slurry for Example 2

Ingredient	Quantity	Wt.%
Demi water	100	25
PEG4000	28	7
Dolapix	6	1.5
Ammonia	5.2	1.3
CMC	0.8	0.20
Ti powder	264	66
Total	404	

- 20 Using this slurry, the procedure of Example 1 was repeated. Of the obtained porous titanium, microscopic photographs were taken as shown in Figs. 6-9. Fig. 6 shows the structure of porous titanium under SEM. Fig. 7 shows the strut of porous titanium, Fig. 8 shows microstructure at a magnification of 500x, and Fig. 9 shows the same microstructure at a higher magnification (1000x).

Again the pictures show a interconnected system of regularly shaped pores.

The porous structures obtained in both Example 1 and 2 had a mechanical compressive strength of 10 MPa (as measured on a Hounsfield test bench at 1 mm/min), which is sufficient for load bearing purposes in implant applications.

Claims

(40)

1. Method for preparing a porous body, suitable for the production of a porous metal article, comprising the steps of providing a polymeric foam, which foam is impregnated with a slurry of metal particles, drying the impregnated foam, followed by pyrolysis in the presence of metal hydride
5 particles.
2. Method according to claim 1, further comprising sintering of the porous body, which sintering is carried out in the presence of metal hydride particles.
3. Method according to claim 1 or 2, wherein the presence of said metal
10 hydride particles is provided by placing metal hydride particles in the environment without contacting said impregnated foam in which said pyrolysis or said sintering is carried out.
4. Method according to any of the previous claims, wherein said metal is selected from titanium, tantalum, titanium alloy, tantalum alloy, cobalt-
15 chromium, stainless steel, nickel and nickel alloy, zirconium, niobium and mixtures thereof.
5. Method according to any of the previous claims, wherein said metal hydride is based on the same metal as said metal particles.
6. Method according to any of the previous claims, wherein said
20 polymeric foam comprises polyurethane.
7. Method according to any of the previous claims, wherein said slurry further comprises one or more of the following additives: a binder, a defloculant, a viscosity modifying agent and/or a pH-modifying agent.
8. Method according to claim 7, wherein said slurry comprises a binder
25 selected from PEG4000, methylcellulose and/or carboxyl methyl cellulose (CMC).
9. Method according to any of the previous claims, wherein said metal particles have a mean diameter of 5-100 μm .

10. Method according to any of the previous claims, wherein said pyrolysis is carried out at a pressure of 10^{-3} - 10^{-2} mbara
11. Method according to any of the previous claims, wherein said sintering is carried out at a pressure of 10^{-6} - 10^{-4} mbara.
- 5 12. Method according to any of the previous claims, wherein said pyrolysis is carried out at a temperature of 150 to 550°C.
13. Method according to any of the previous claims, wherein said sintering is carried out at a temperature of 1050-1350°C.
14. Article of manufacture comprising a porous body obtainable by a
10 method according to any of the previous claims.
15. Article according to claim 14, which is a medical implant, preferably a bone replacement material or a scaffold.
16. Medical implant comprising a porous metal structure with a porosity of at least 50%, having a mean pore size of at least 400 μm , wherein the pores
15 are interconnected, which implant has a compressive strength of at least 10 MPa, wherein the metal is selected from titanium, tantalum, titanium alloys, tantalum alloys and combinations thereof.
17. Use of a metal hydride in a sintering and/or pyrolysis process for the manufacture of porous metal articles from metal particles.

Title: Porous metals for implants

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19. 02. 2001

(40)

Abstract

The invention is directed to a method of preparing porous metals, as well as to these porous metals per se. More in particular the invention is directed to the use of these porous metals in the preparation of medical items, such as implants.

According to the method of the invention, a polymeric foam is impregnated with a slurry of metal particles, such as titanium, tantalum, titanium alloy or tantalum alloy particles. The impregnated foam is subsequently dried and subjected to pyrolysis and subsequent sintering. Due to the presence of metal hydrides, the formation of undesired compounds, such as metal oxides or nitrides, is avoided.

The products obtained are highly suitable for medical implants.

Figure 1 The structure of porous titanium under an optical microscope

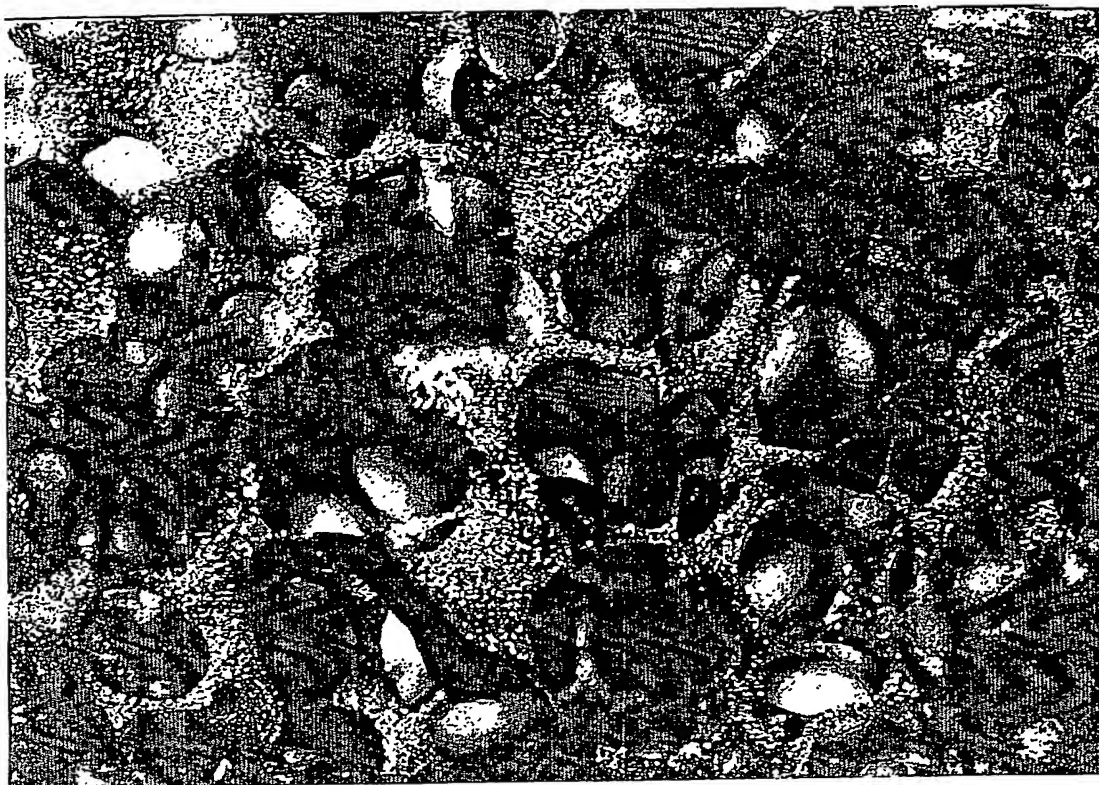


Fig. 2 The structure of porous titanium under SEM

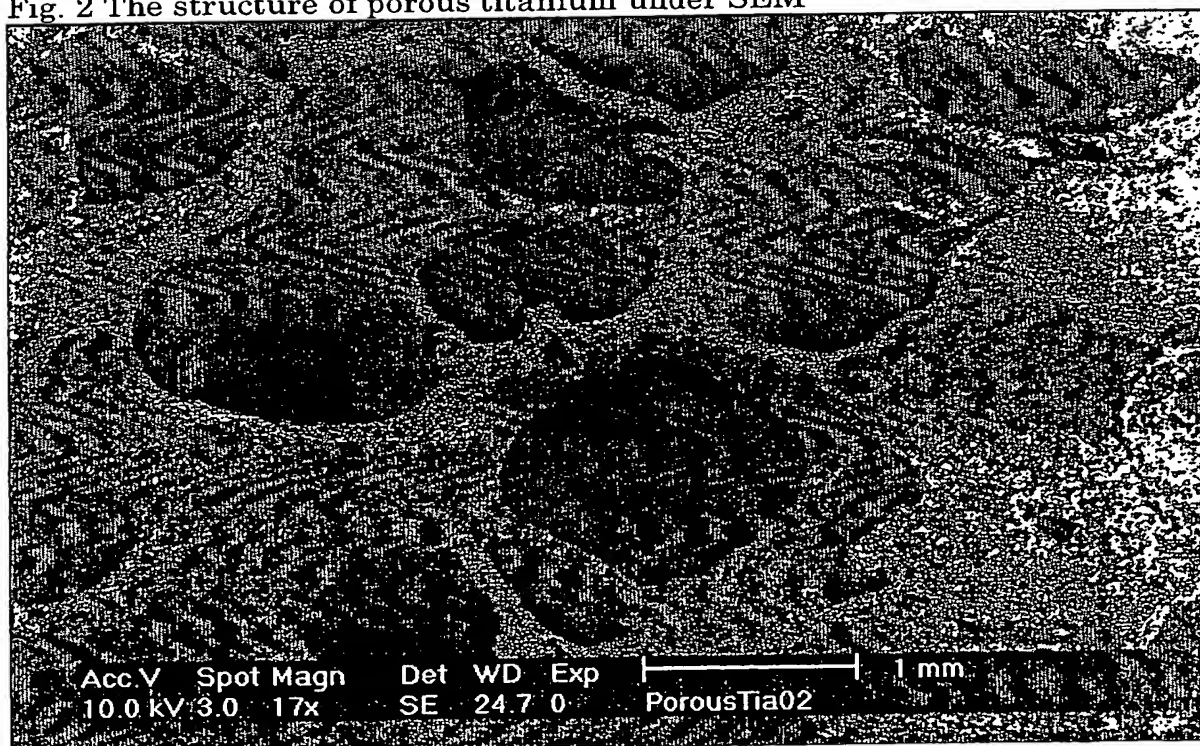


Fig. 3 The strut of porous titanium under SEM

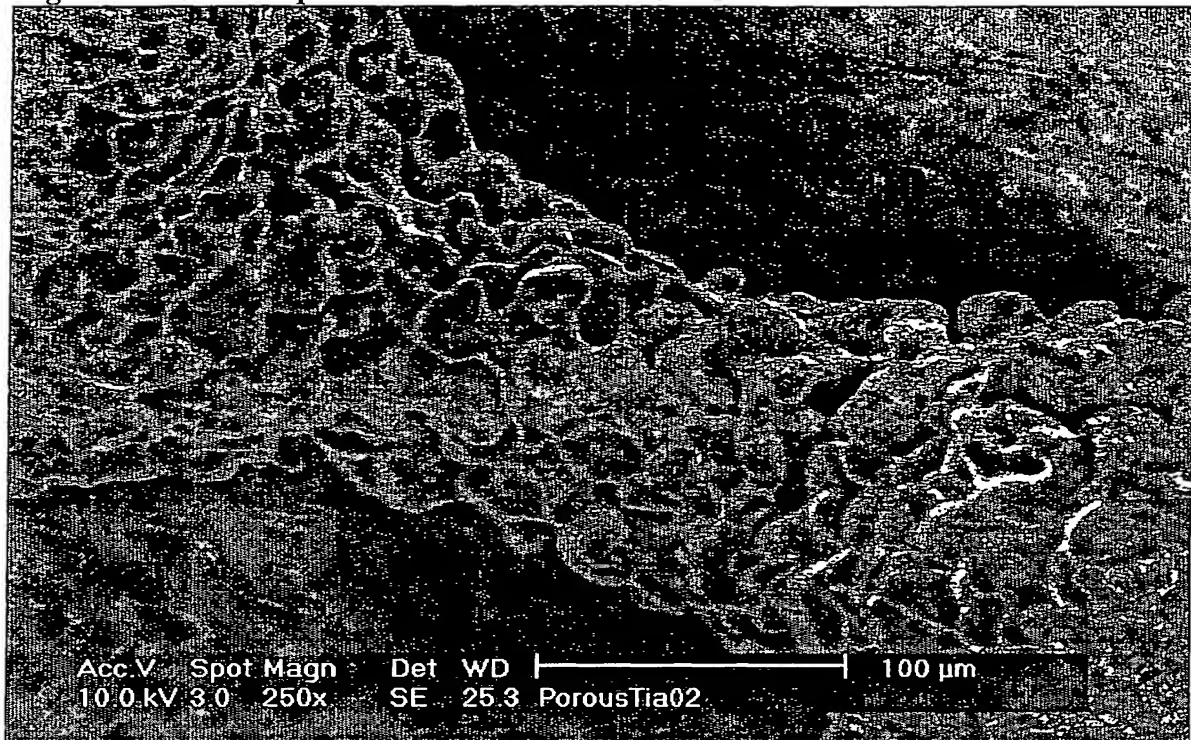
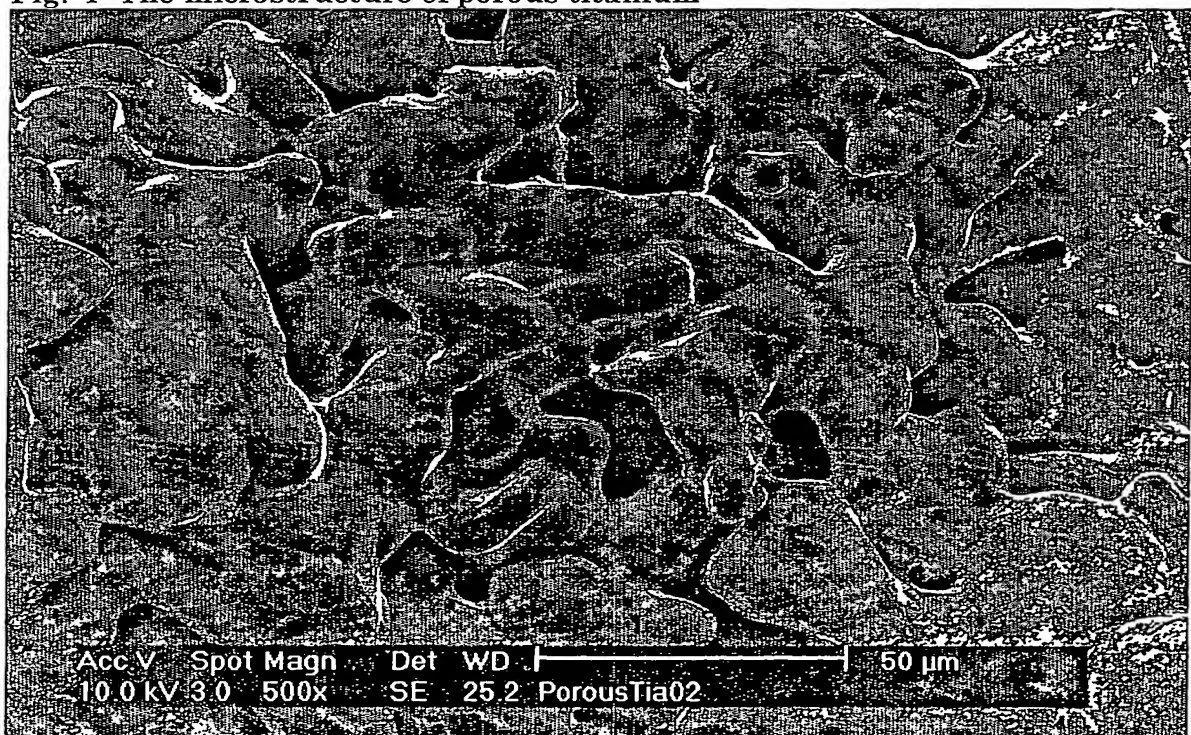


Fig. 4 The microstructure of porous titanium



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Fig. 5 The microstructure of porous titanium at a high magnification

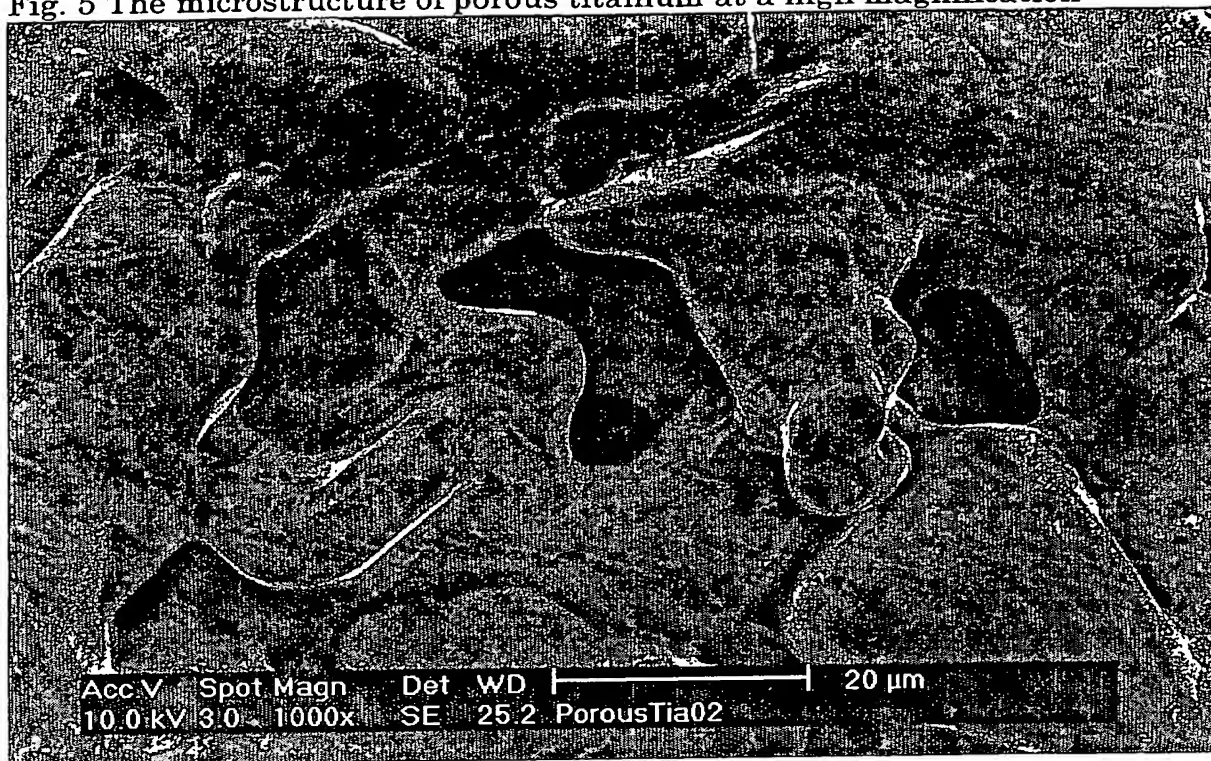


Fig 6 The structure of porous titanium under SEM

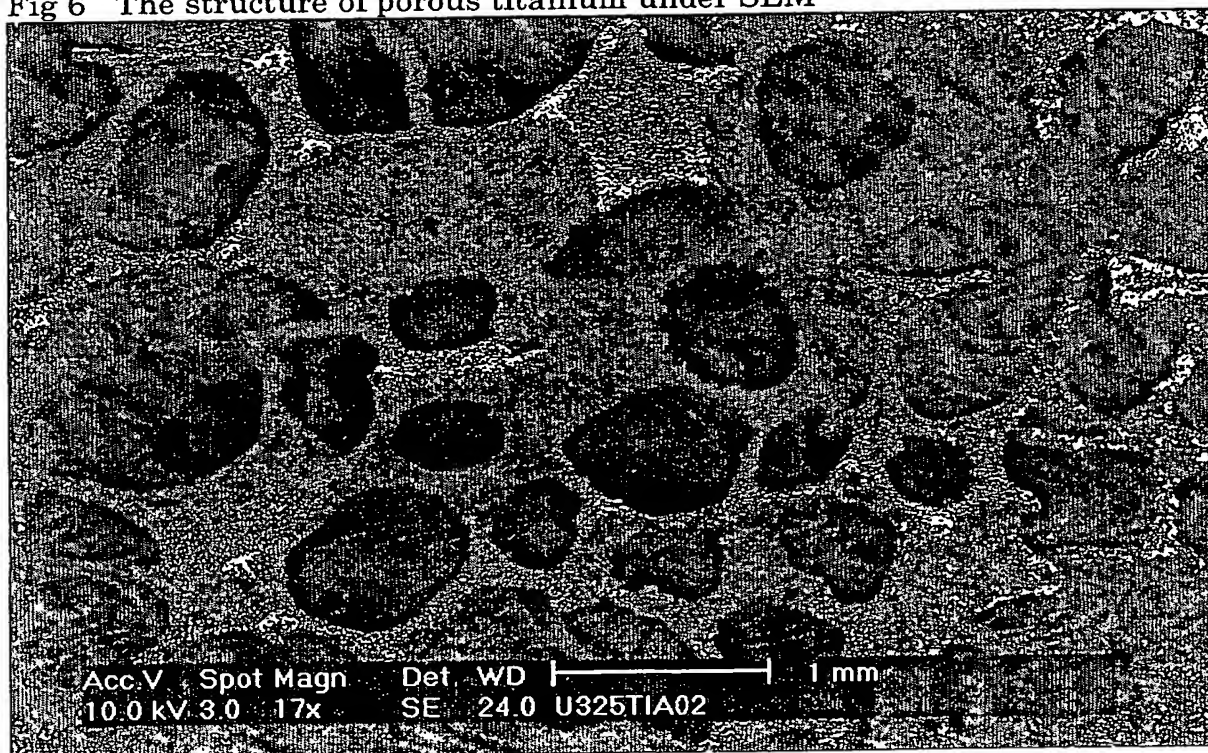


Figure 7 The strut of porous titanium at a high magnification

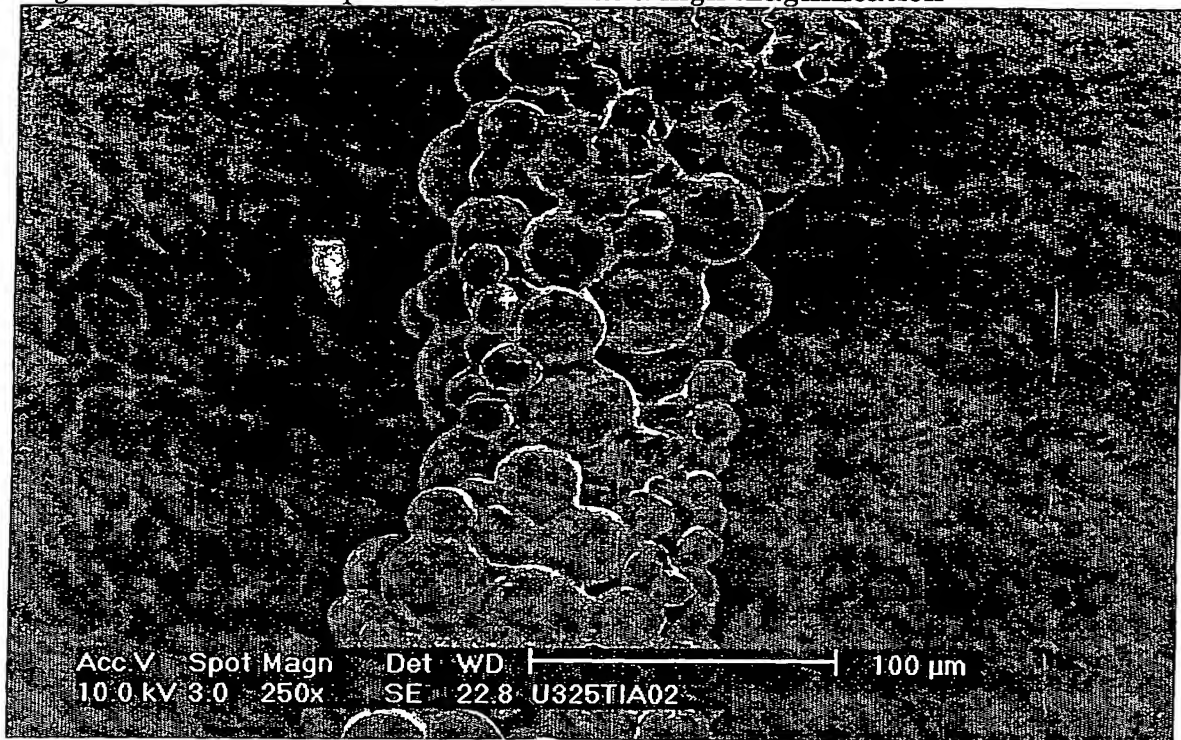
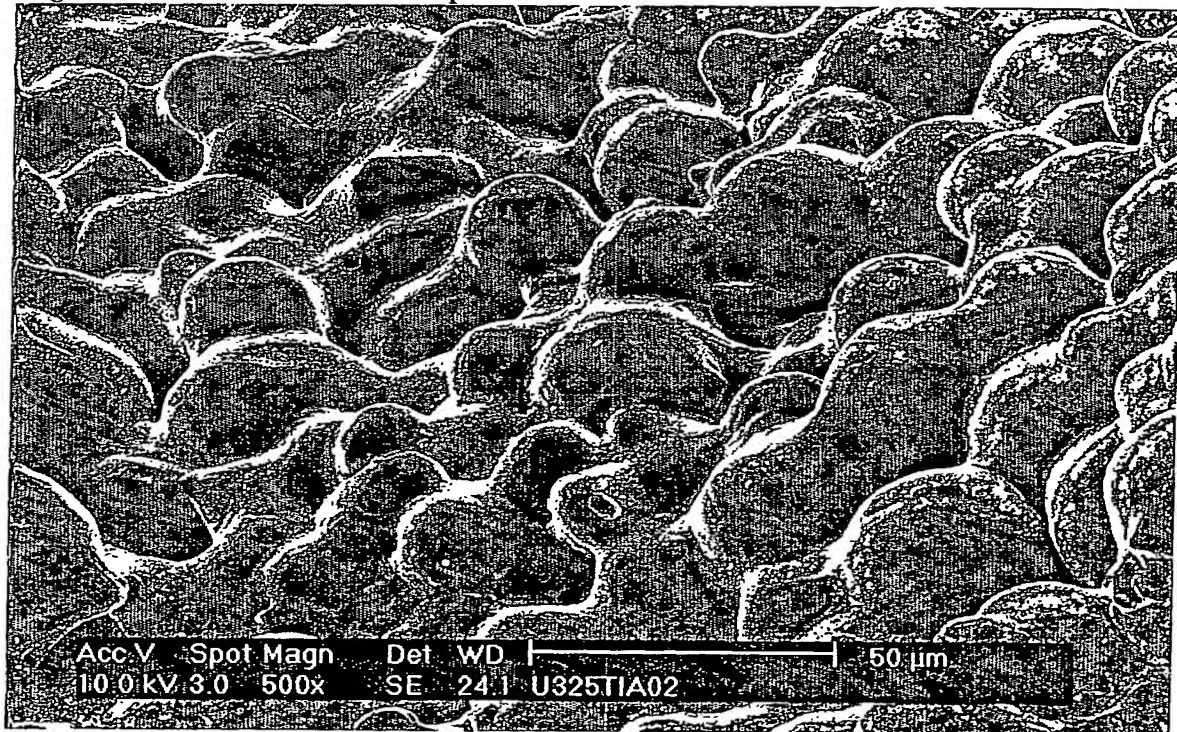
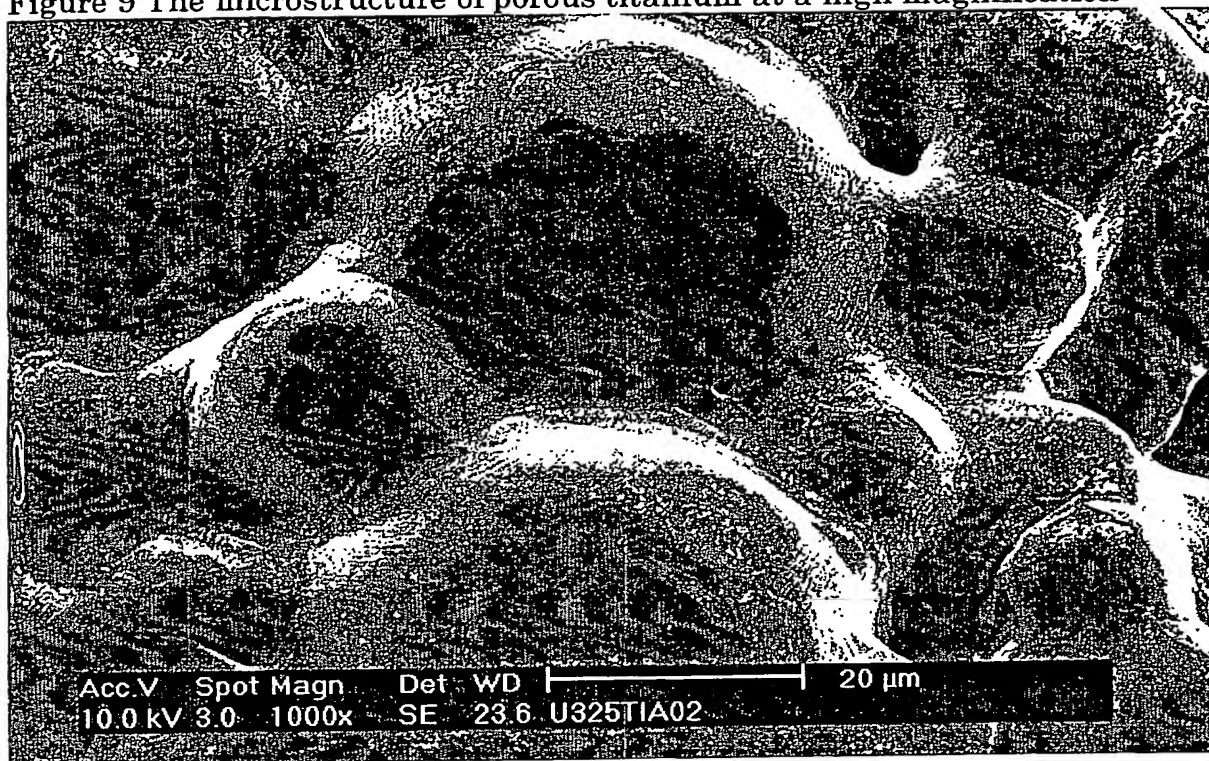


Fig. 8 The microstructure of porous titanium



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Figure 9 The microstructure of porous titanium at a high magnification



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